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BRL D/A ltr, 4 Apr 1974

BRL-MR-1088
AD0149358

BRL

MEMORANDUM REPORT NO. 1088

A SIMPLE MECHANICAL METHOD FOR MEASURING THE REFLECTED IMPULSE OF AIR BLAST WAVES

by

O. T. Johnson
J. D. Patterson, II
W. C. Olson

July 1957

U. S. ARMY MATERIEL COMMAND
BALLISTIC RESEARCH LABORATORIES
ABERDEEN PROVING GROUND, MARYLAND

B A L L I S T I C   R E S E A R C H   L A B O R A T O R I E S

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Department of the Army Project No. 5B0305010
Ordnance Research and Development Project No. TB3-0238

A B E R D E E N   P R O V I N G   G R O U N D,   M A R Y L A N D

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MEMORANDUM REPORT NO. 1088

OTJohnson/JDPatterson, II/WCOlson/rfw
Aberdeen Proving Ground, Md.
July 1957

A SIMPLE MECHANICAL METHOD FOR MEASURING THE REFLECTED IMPULSE OF AIR BLAST WAVES

ABSTRACT

A mechanical method is described for measuring the impulse imparted to a flat rigid surface by the reflection (at 90° or normal incidence) of an air blast wave. The method consists of measuring the velocity at which a cylindrical plug of known mass is projected from a hole in a large rigid surface by a normally incident blast wave and computing the impulse from Newton's 2^{nd} law.

Experimental results were obtained for spherical Pentolite explosive charges ranging in weight from 1/4 to 2 lbs and scaled distances from 0.5 to 2.5 ft/lb$^{1/3}$. Results of 154 trials are tabulated and also presented graphically. In addition, a comparison is made with data obtained with piezoelectric gages.

TABLE OF SYMBOLS

$Z = R/w^{1/3}$	- scaled distance (R in feet, w in lbs)
A	- area of the top of the plug in in^2
t	- time in seconds
p(t)	- excess pressure in blast wave as a function of time
T	- duration of positive phase of blast wave, i.e., the time at which the excess pressure falls to zero
g	- acceleration due to gravity, 32.17 ft/sec^2
m	- mass of the plug in slugs
x	- displacement in feet
I	- impulse in $lb\text{-}sec/in^2$
P_r	- reflected peak pressure in blast wave for 90^o incidence, psi
w_p	- weight of the plug in pounds
w_e	- weight of the explosive charge in pounds
I_f	- impulse in lb ms/in^2 calculated from film data
I_c	- impulse calculated in lb ms/in^2 from the counter data
σ	- standard deviation of the measured impulse in lb ms/in^2

INTRODUCTION

Blast vulnerability studies conducted by these Laboratories include the investigation of the response of both simple and complex structures to blast loading.[1*] Before relationships can be established concerning the loading of structures by blast, it is necessary to know the values of those blast parameters responsible for deformation or destruction of the structures. Two sets of important parameters are: (1) the peak pressure and positive impulse produced in free undisturbed air (i.e., with no reflecting or interfering surfaces present), and (2) the peak pressure and positive impulse transmitted to an infinite rigid wall. Pressures and impulses measured in free air (with no reflection) are designated as "side-on", and those measured on the surface of a rigid wall (with reflection at 90° incidence) are designated as "face-on." Some measurements of these parameters have been made previously[2] and have been applied[3] to problems of air blast damage to aircraft.

Attempts to correlate damage to aircraft structures with blast parameters indicate that the important parameter to consider for internal blast is probably the normally reflected impulse.[4] Recently, a series of firings[3a] using face-on piezoelectric gages as detectors yielded satisfactory reflected impulse data down to a scaled distance (Z) of about 1.5 ft/lb$^{1/3}$. Inadequate mechanical response of the gages closer to the explosive charge resulted in a prohibitively large scatter in the measurements. Since a major portion of internal blast studies within aircraft structures deals with scaled distances ranging from 1.5 down to 0.5, it was desirable to find some means other than the complex piezoelectric gage technique for obtaining experimental data in this region.

An experiment based on Newton's 2nd law was devised. In the center of a steel plate mounted horizontally several feet above the ground provision was made for an adapter to accommodate a small cylindrical plug

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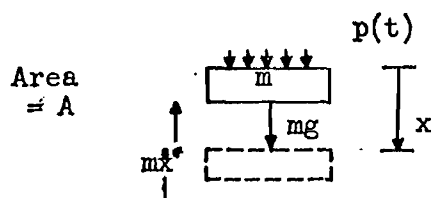
* Superscripts refer to references listed at the end of report.

slightly less than one inch in diameter and about one and one-half inches long. The blast wave from an explosive detonated above the plug imparted a downward velocity to the plug. The known mass (m) of the plug and its measured average velocity over a predetermined distance were sufficient to determine the impulse from the consideration of the simple equations of rigid-body motion derivable from Newton's 2nd law. It is the purpose of this report to present the theory and the experiment for obtaining blast impulse by the "plug technique," and to discuss the uses and limitations of the method.

THEORY

Presume, for the purposes of analysis, that the plug is a rigid cylinder held as an element of a rigid infinite reflecting plate until the instant that a normally incident air blast wave impacts on the plate surface. At this instant, the plug is no longer held in place but is allowed to assume free-body motion under the effects of gravity and the pressure in the blast wave. If frictional effects are neglected, the equation of motion during the time of the blast pressure phase is:



$$A\,p(t) + mg = m\ddot{x} \qquad (1)^*$$

$$\text{for } 0 < t \leq T$$

Velocity-time and displacement-time histories of the motion can be obtained by integrating equation (1), using the initial conditions that the plug displacement and velocity are zero. The velocity is given by

$$\dot{x} = gt + \frac{A}{m}\int_0^t p(t)\,dt \qquad (2)$$

and the displacement by

$$x = \frac{gt^2}{2} + \frac{A}{m}\int_0^t \int_0^t p(t)\,dt\,dt \qquad (3)$$

---

* Dots indicate derivatives with respect to time.

The velocity and displacement at the end of the pressure pulse are obtained by substituting the pulse duration, T, in these equations. The integral in equation (2) then represents the usual definition of the blast wave impulse.* Or,

$$I = \int_0^T p(t)\ dt = \frac{m}{A} \left[\dot{x}(T) - gT\right] \tag{4}$$

After the blast pressure returns to ambient, the equation of motion is merely that of a body freely falling in a gravity field, or

$$\ddot{x} = g \quad \text{for} \quad t \geq T \tag{5}$$

Integration of this equation and use of the final velocity and displacement from equations (2) and (3) respectively as initial conditions yield

$$\dot{x} = gt + \frac{A}{m} I \tag{6}$$

and

$$x = \frac{gt^2}{2} + \frac{A}{m} I\ (t - T) + \frac{A}{m} \int_0^T \int_0^t p(t)\ dt\ dt \tag{7}$$

If $t >> T$ and the displacement at the end of the blast pulse is small, the last equation reduced to

$$x = \frac{gt^2}{2} + \frac{A}{m}\ It \tag{7a}$$

Equations (6) and (7a) show that the impulse can be readily inferred from measurement of velocity or displacement at some time after onset of the blast wave. Equation (7a) can be rearranged as

$$I = \frac{m}{A} \left(\frac{x}{t} - \frac{gt}{2}\right) \tag{8}$$

---

* It is assumed that the perturbation of the blast wave by motion of the plug is not significant, i.e., the energy transferred to the plug is small compared to the energy transported by the blast wave to the plug surface.

If the time origin is known, this equation yields the approximate impulse directly by a simple measurement of the time taken for the plug to travel a known distance.

Equations (6) and (7a) can also be used to compute the impulse if the plug is observed at two positions a known time interval apart. Displacements at times t_1 and t_2 are given by

$$x_1 = \frac{gt_1^2}{2} + \dot{x}_o t_1$$

and

$$x_2 = \frac{gt_2^2}{2} + \dot{x}_o t_2$$

where

$$\dot{x}_o = \frac{A}{m} I$$

Combination of these equations yields the relation that

$$\dot{x}_o = \frac{x_2 - x_1}{t_2 - t_1} - \frac{g}{2} (t_2 + t_1)$$

Now,

$$\dot{x}_1 = \dot{x}_o + gt_1 = \frac{x_2 - x_1}{t_2 - t_1} - \frac{g}{2} (t_2 - t_1) \tag{9}$$

The velocity at time t_1 is given by equation (9) in terms of the time interval, $t_2 - t_1$, for the plug to travel distance $x_2 - x_1$. The initial velocity, $\dot{x}_o = \frac{A}{m} I$, is then computed from

$$\dot{x}_o = \frac{A}{m} I = \sqrt{\dot{x}_1^2 - 2gx_1} \quad , \tag{10}$$

which is obtained by a simple combination of equations (6) and (7a).

Note that the accuracy of equations (8), (9), and (10) for computing the impulse is dependent on the accuracy of the assumptions that the displacement at the end of the pressure pulse is small and that frictional effects including air drag forces can be neglected.

The accuracy of the assumption of small plug displacement at the end of the pressure pulse can be estimated from equation (3). For simplicity, assume that the pressure-time history, is given by $P_r\ (1 - \frac{t}{T})$, for $0 < t \leq T$. Then, the displacement at the end of the pulse is:

$$x(T) = \frac{gT^2}{2} + \frac{A}{m} P_r \frac{T^2}{3} = \frac{gT^2}{2} + \frac{A}{m} \frac{2}{3} IT \tag{11}$$

The longest duration blast wave encountered during these tests (from the 2-lb charges at Z = 2.5) lasted only 1.6 ms,* giving a displacement for the first term on the right side of (11) of less than 5×10^{-4} inches. This term can therefore always be neglected, and Eq. (11) approximated by

$$x(T) = \frac{A}{m} \frac{2}{3} IT \tag{11a}$$

from which a reasonable estimate of the displacement can be computed.

A calculation of the reduction in velocity due to air drag indicates that it is reasonable to assume that the effect is negligible.

EXPERIMENTAL SETUP AND PROCEDURE

Experimental Setup

The experimental setup was designed to simulate as closely as possible the desired conditions of subjecting a free plug in an infinite, rigid plane to a normally incident blast wave.

In order to simulate an infinite rigid plane, a 1" thick rectangular steel plate was mounted approximately 6 ft. above the ground level as indicated in Figure 1. The plate was supported by steel pipes with the base of each pipe embedded in concrete. The flat surface was large enough to prevent diffraction effects from modifying the positive phase of the blast wave. Three sides were enclosed to prevent diffractive shock wave disturbances from reaching the underside of the plug before the plug velocity could be recorded. An overhang on the open side was sufficient to prevent any disturbances from reaching the plug from that side during the recording period.

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* See ref. 3a, Fig. 5, for data on duration, T.

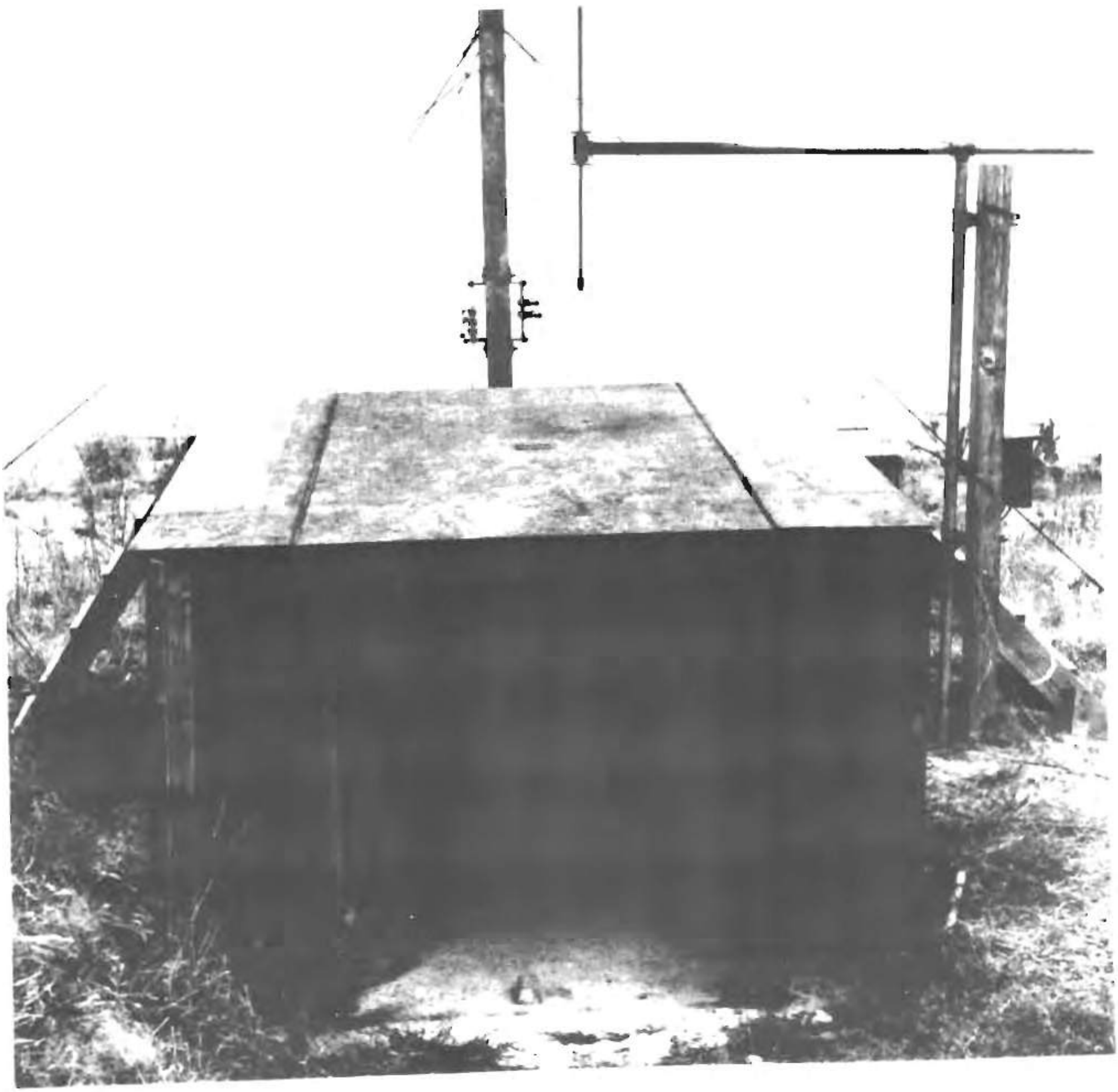


Figure 1

The plug was mounted in a plug adapter hole in the plate, figure 2. The plug adapter, Figure 3, consisted of a threaded housing enclosing a formed coil of copper wire. When the coil was energized the magnetic field generated held a cylindrical, steel banded, one-inch diameter fibre plug in position with the plug top surface flush with the surface of the plate. A secondary mechanism held the plug in place until the coil was energized (Figure 4). This mechanism was a safety feature incorporated to assure that there was no danger of the coil energizing current prematurely detonating the explosive while it was being positioned.

The spherical Pentolite explosive charge was positioned as shown in Figure 5, with the explosive resting on a fiber tube fitted over the end of the vertical adjustment rod of the mount. The mount was designed to allow rapid and positive positioning of the charge.

For optical measurements of plug motion, a scale, Figure 6, was mounted on the rear wall of the plug facility indicating the distance in inches from the underside of the plate to the concrete floor. The scale was located in a vertical plane six inches behind the path of the plug. Floodlights were mounted on the steel supporting pipes to furnish illumination adequate for photography. The plug was painted black to give maximum contrast with the white background of the scale board.

The plug motion was observed by an Eastman high speed camera equipped with a neon timing light, pulsed at 1,000 cps from a frequency standard, which impressed timing marks on the edge of the film. Thus, time axis calibration was obtained by photographing the pulsed light simultaneously with the record of the plug flight.

A second scheme for measuring the time taken by the plug to travel between two fixed points was to use Potter electronic counter chronographs. A barium titanate time-of-arrival gage, Figure 7, which was threaded into a nut welded to the underside of the plate in the vicinity of the coil adapter, sensed the blast wave as it struck the plate and started a Potter counter. A similar gage on the underside of a small dural plate, mounted near the concrete floor, Figure 8, detected the plug striking the plate

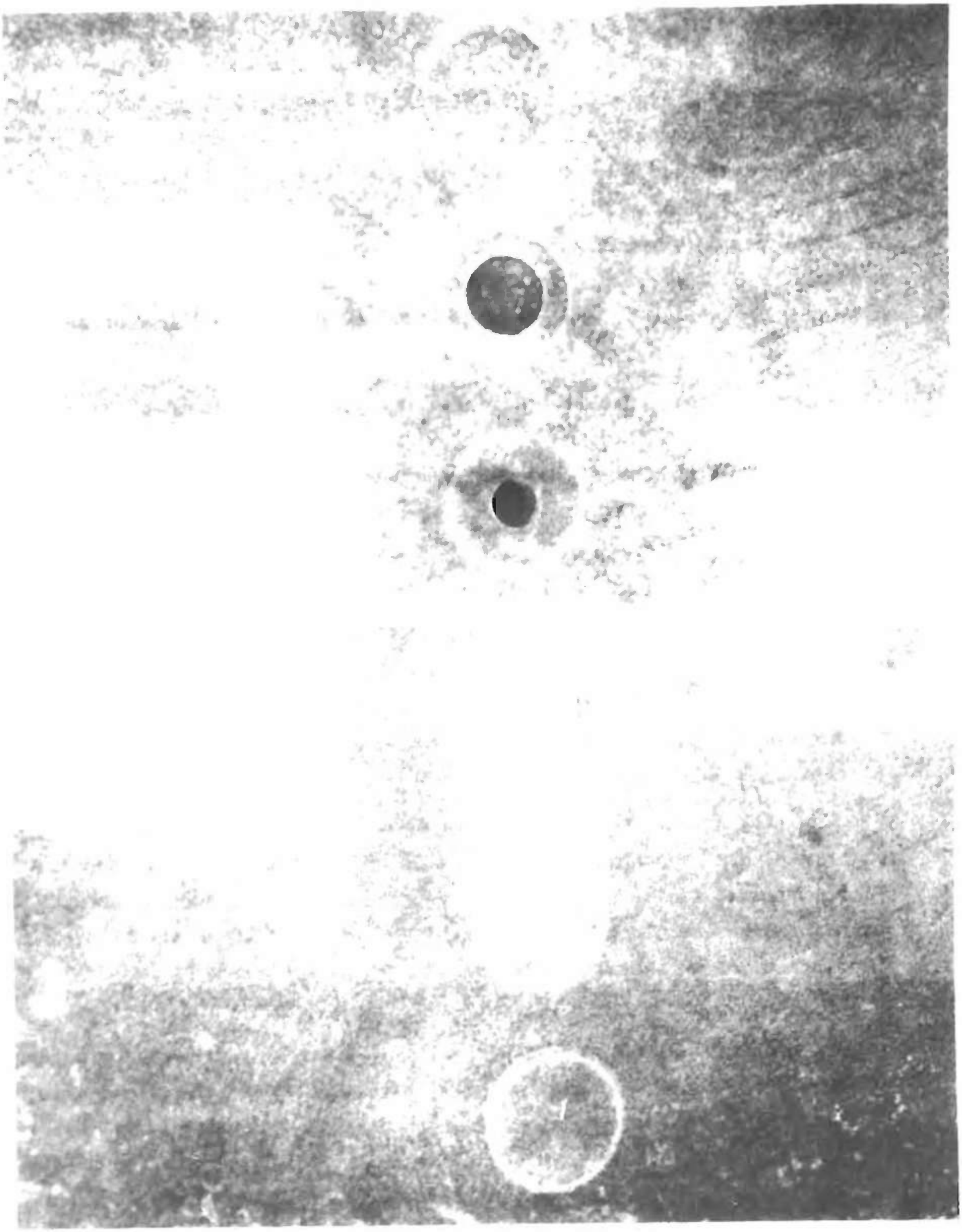


Figure 2

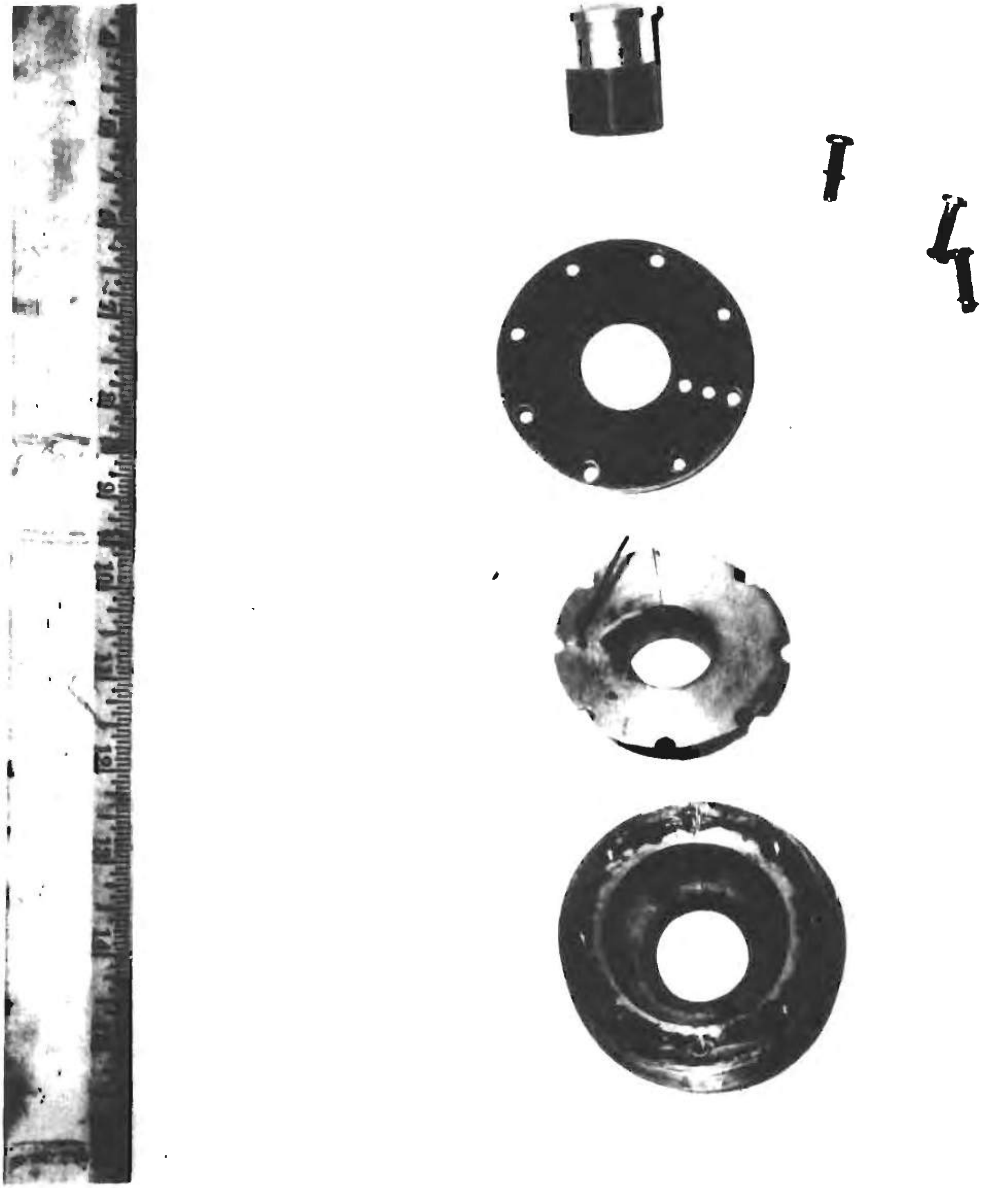


Figure 3

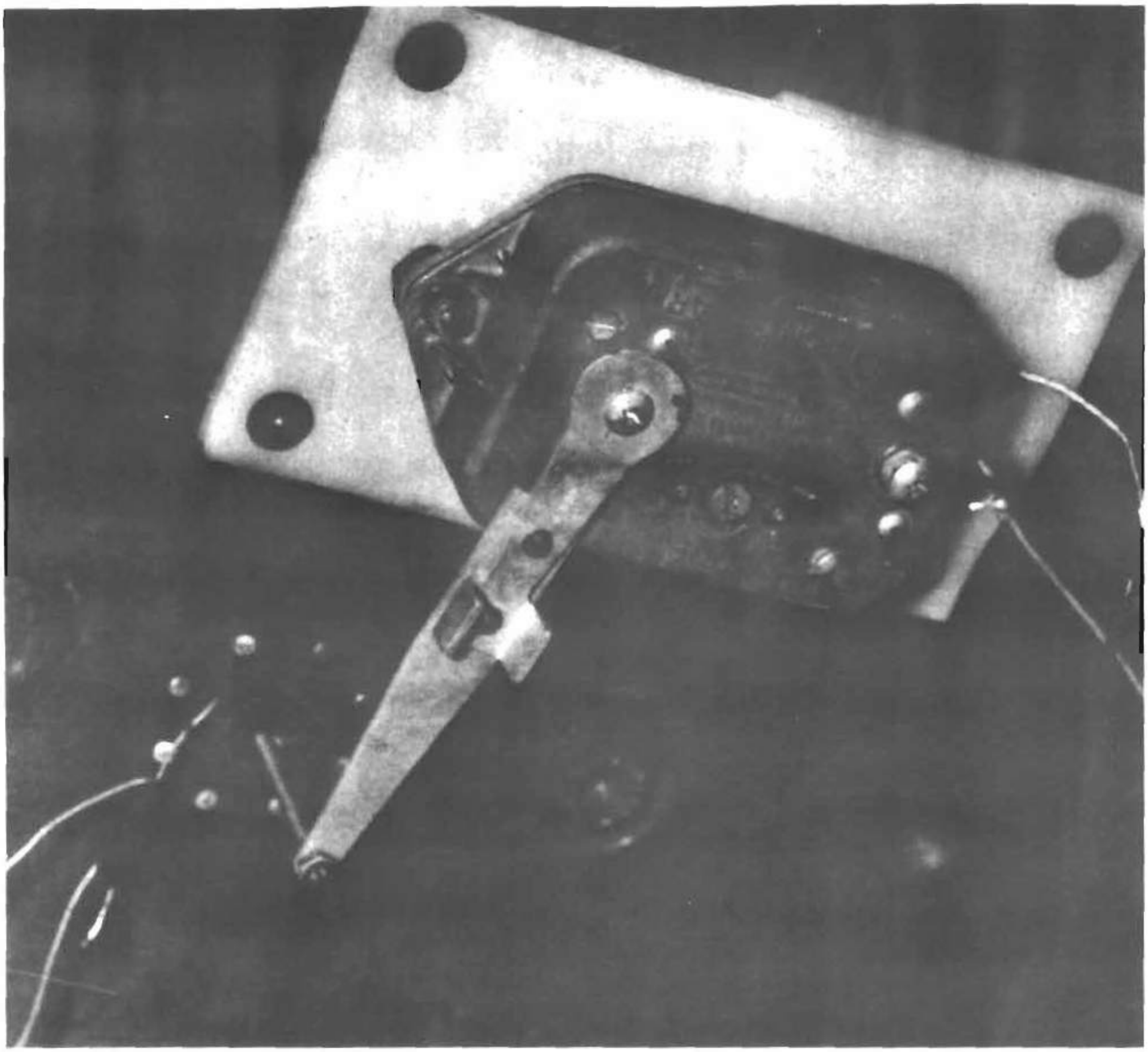


Figure 4

Figure 5

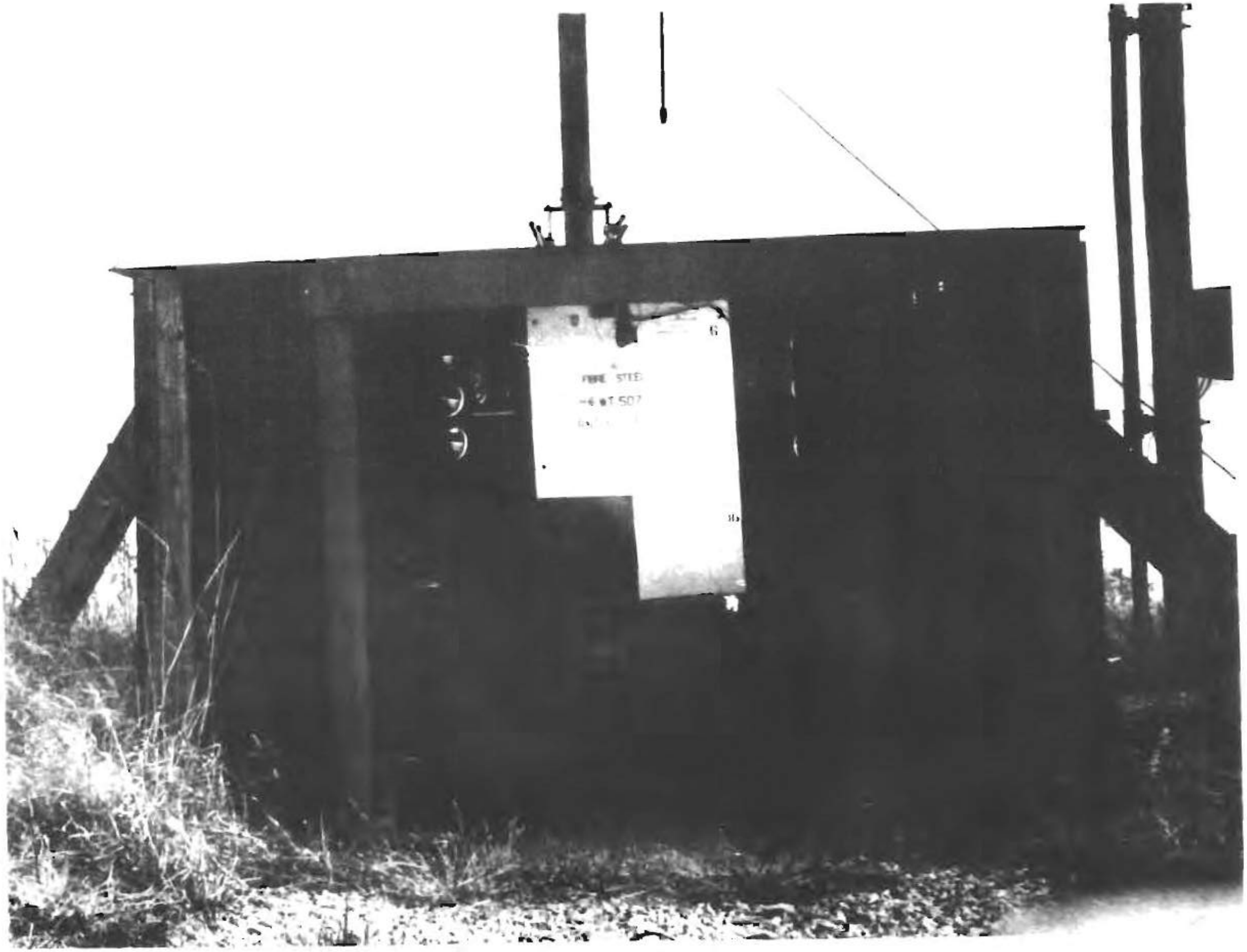


Figure 6

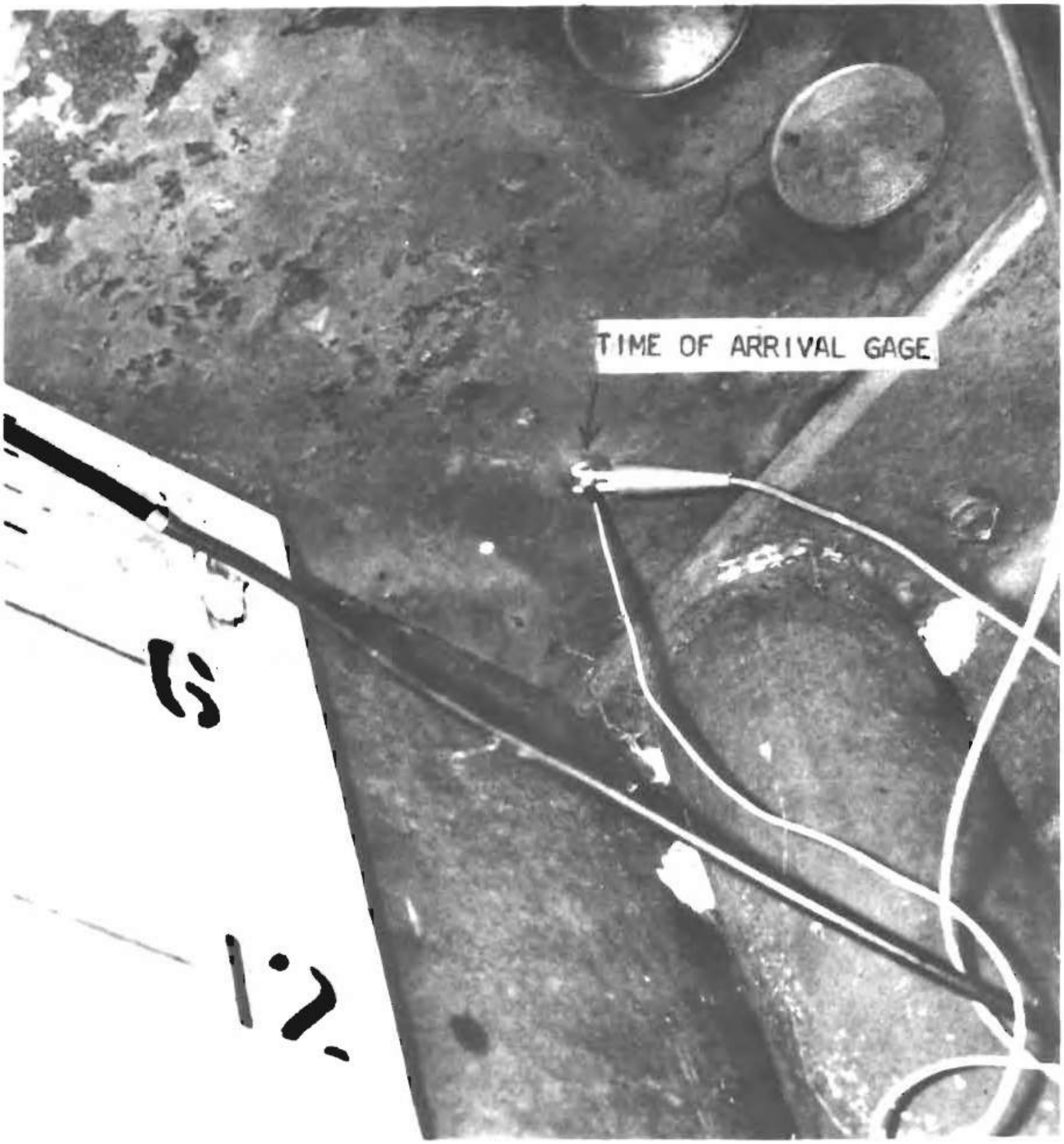


Figure 7

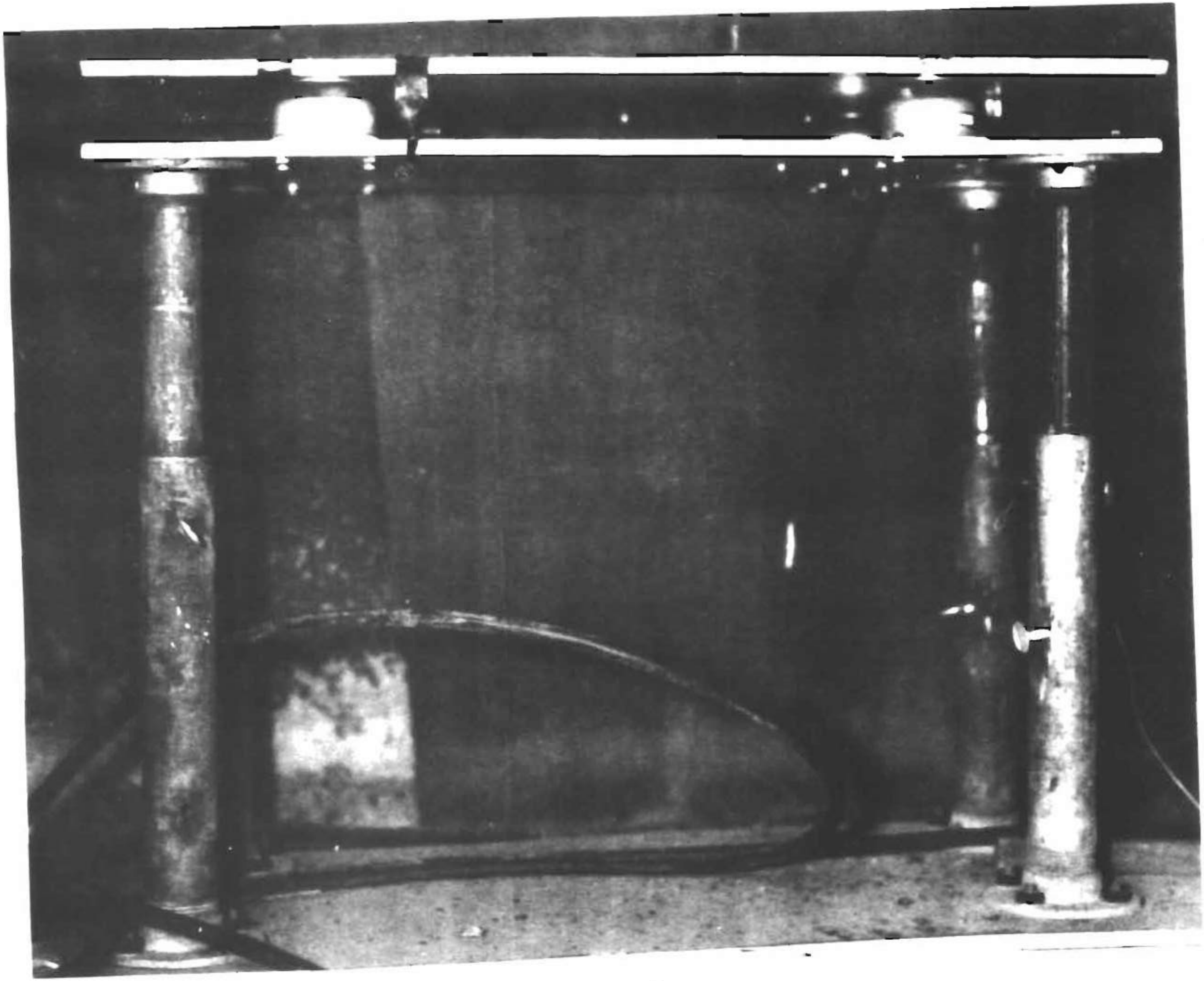


Figure 8

and stopped the counter.

Events in each test firing were automatically sequenced by an electronic sequence timer. This timer, the Eastman camera and its timing circuitry, and other associated equipment were housed in an instrument shelter (Figure 9) about 30 ft away from the plug facility and facing its open end.

Each test firing was controlled from a bomb-proof shelter several hundred feet from the test site. The shelter contained the electronic counter chronographs, firing circuit controls, and safety circuits (see Figure 10). A schematic of the entire test circuitry is given in Figure 11.

Test Procedure

The plug was inserted in the plug adapter and held in position by the arm of the plug-holding solenoid (Figure 4). The explosive was then mounted (Figure 5) and its location carefully measured. The Eastman camera was loaded and cocked, the counter chronographs reset, firing circuit completed, and personnel cleared from the test area.

The electro-magnet in the adapter (Figure 3) was then energized to hold the plug and the plug-holding solenoid energized to move its arm out of the path of motion.

The remote sequence timer starting circuit was then energized. The sequence timer started the Eastman camera, turned on the displacement scale illuminating lamps, and then simultaneously released the plug and detonated the explosive. The displacement-time history of the plug was recorded by the Eastman camera; the time interval from impact of the shock wave on the reflecting plate to arrival of the plug at the base plate 4.75 ft below was recorded by Potter electronic counters.

ANALYSIS AND RESULTS

Equations (8), (9) and (10) can be directly applied to computation from the test data of the reflected impulse in the blast waves. Displacements x_1 and x_2 are measured from enlargements of selected single frames of the Eastman camera motion pictures, with slight corrections for parallax

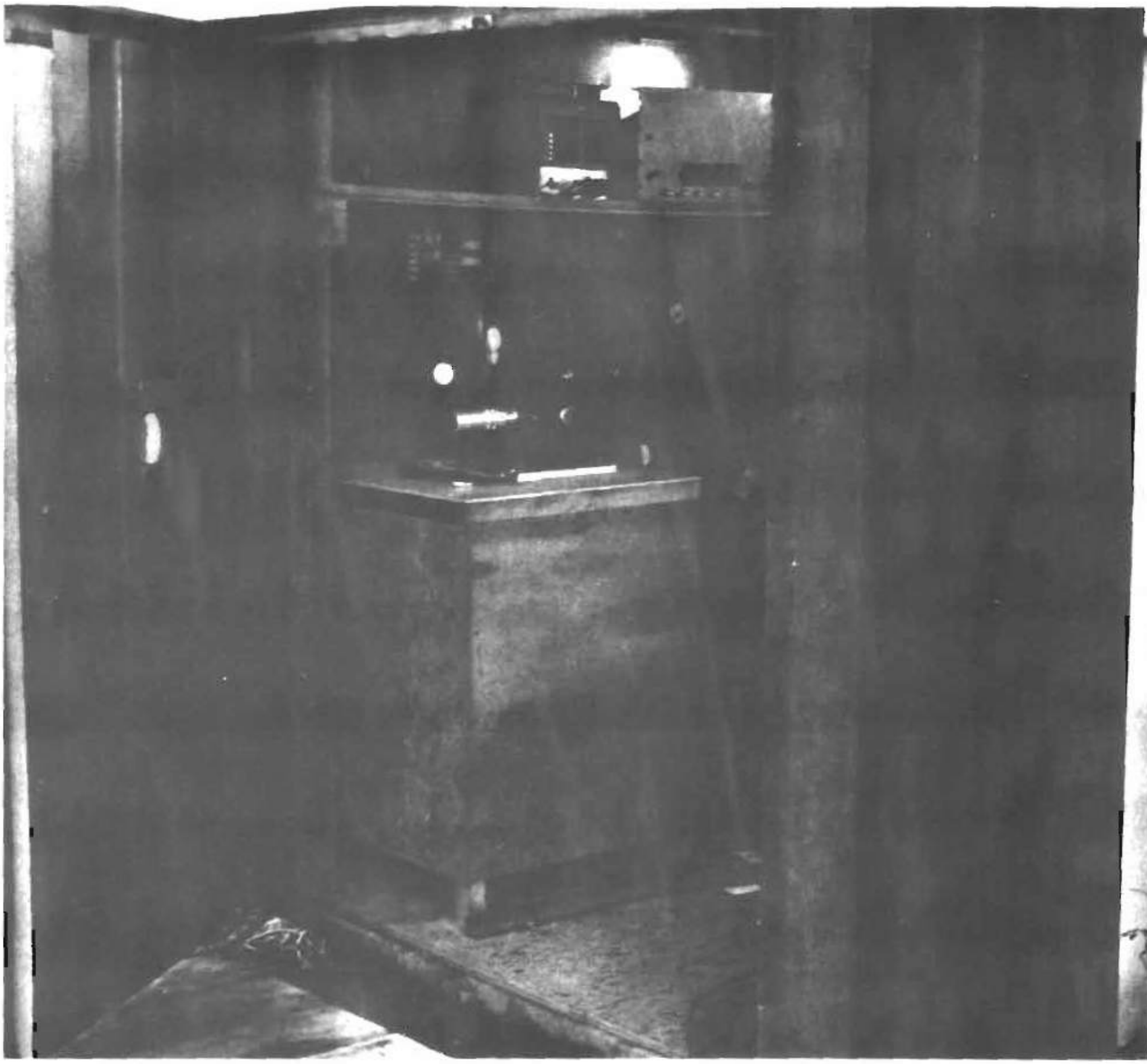


Figure 9

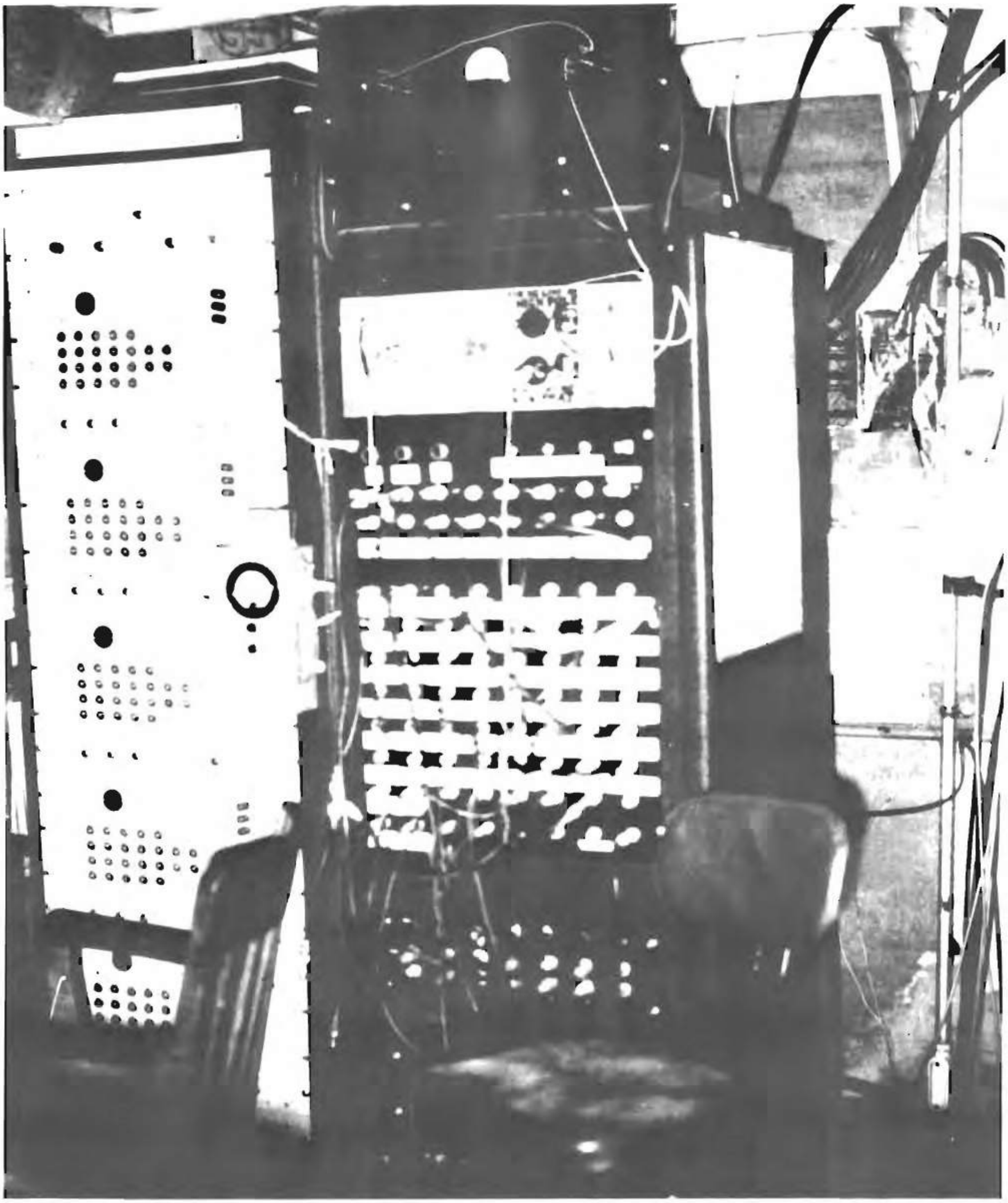
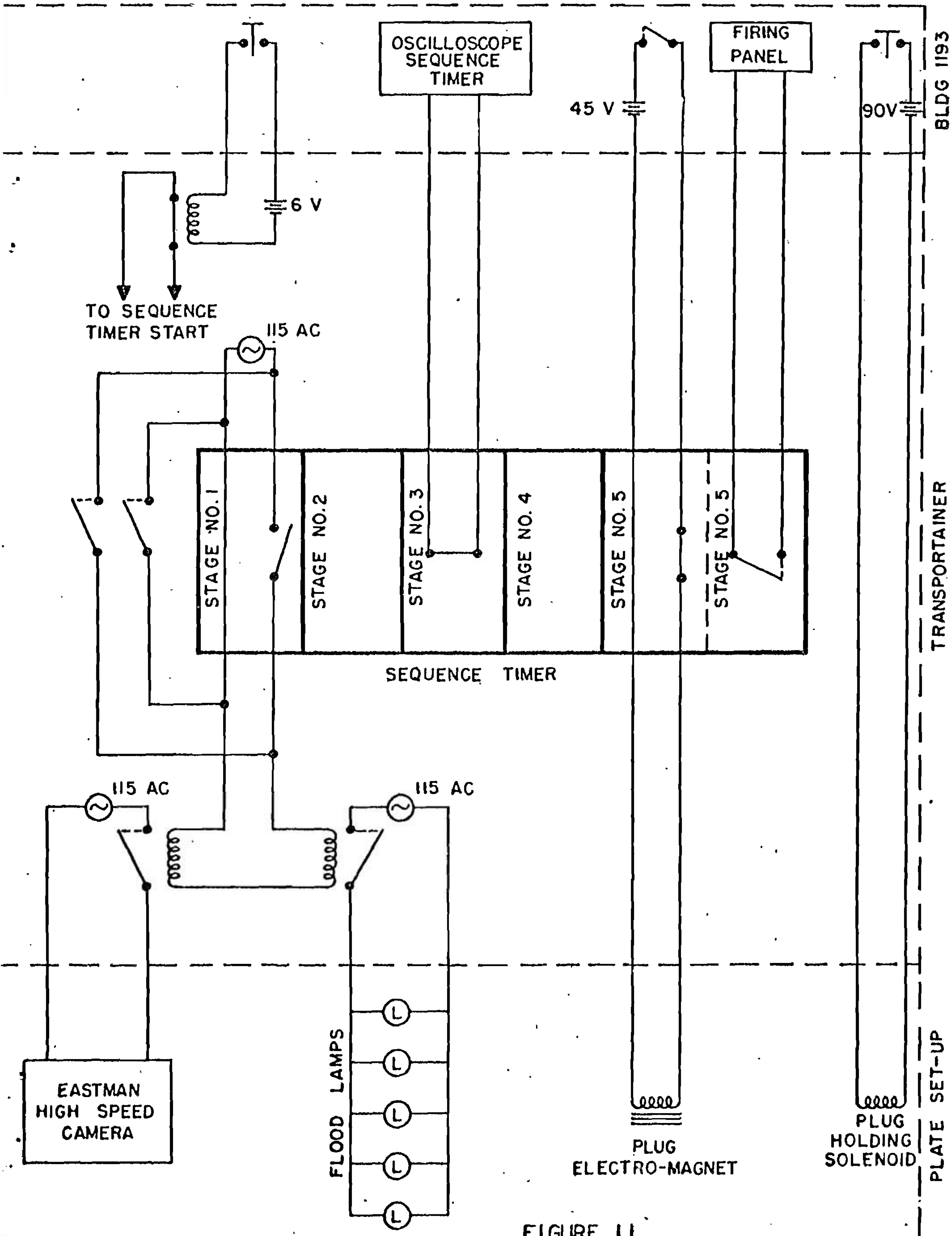


Figure 10



OSCILLOSCOPE SEQUENCE TIMER
FIRING PANEL
45 V
90V
BLDG 1193
6 V
TO SEQUENCE TIMER START
115 AC
STAGE NO. 1
STAGE NO. 2
STAGE NO. 3
STAGE NO. 4
STAGE NO. 5
STAGE NO. 5
SEQUENCE TIMER
TRANSPORTAINER
115 AC
115 AC
FLOOD LAMPS
L
L
L
L
L
EASTMAN HIGH SPEED CAMERA
PLUG ELECTRO-MAGNET
PLUG HOLDING SOLENOID
PLATE SET-UP

FIGURE 11

being applied. The time interval between the frames, $t_2 - t_1$, is obtained from the 1000 cps timing marks on the edge of the film. Equation (9) yields the plug velocity, $\dot{x}_1$, at position x_1 from these data, and equation (10) multiplied by 1000 the reflected impulse, I_f in lb. ms/in.^{2} The impulse from the counter data is obtained by direct substitution in equation (8).

Table I presents a compilation of the test results. For each scaled distance, Z, in ft/lb$^{1/3}$ the following data are presented:

σ = standard deviation of the measured impulse in lb ms/in^2.

w_e = weight of explosive in lb.

w_p = weight of plug in lb.

δt_f = time interval to travel 0.975 ft. measured from film, milliseconds.

δt_c = time interval to travel 4.75 ft. measured by counter, milliseconds.

$I_f/w_e^{1/3}$ = scaled reflected impulse from film data, lb-ms/lb$^{1/3}$ in^2

$I_c/w_e^{1/3}$ = scaled reflected impulse from counter data, lb-ms/lb$^{1/3}$ in^2

The sets of film and counter impulses in each group were independently examined for erratic observations by a sample criterion for testing outlying observations devised by Grubbs.[5] This test was carried out at the five percent significance level and only 17 observations were discarded from a total of 403.

Since the film and counter impulses were obtained from two different methods of measuring the same physical phenomenon, Student's "t" test* was applied to find if it were feasible to combine the film and counter data into one set of observations for each Z and charge weight. In the case of the 1/4 pound charge at Z = 0.5 the counter readings seemed completely unreliable and were discarded. Although there appears to be a significant difference at the 5% level between the means of the two sets of observations for both the 1/4 and 1/2 pound charges at Z's of 0.75 and 1.50, in the remaining thirteen cases, there was no significant difference. In view of this it was decided to combine the film and counter data in all cases.

---

* The "t" test is a test of the hypothesis that the means of two samples come from the same normal population at a certain level of significance.

TABLE I
Compiled Test Results

$\overline{Z} = .5$

1/4-lb Pentolite (approximately)

Rd. No.	w_e	w_p **	δt_f	δt_c	$I_f/w_e^{1/3}$	$I_c/w_e^{1/3}$
185	.259	.0681	5.59	a	750.77	-- #
186	.256	.0681	5.37	21.40	768.96	940.22
187	.257	.0690	5.50	a	760.00	--
194	.253	.0690	5.66	26.58	741.95	768.61
195	.255	.0690	5.38	36.47	779.32	558.11
196	.255	.0690	5.56	54.01	753.70	374.87
197	.257	.0686	5.23	25.11	794.78	805.20
198	.257	.0677	5.43	a	755.27	--
199	.257	.0677	5.40	25.77	759.54	774.38
200	.259	.0679	5.18	18.71	792.85	1069.2
201	.255	.0681	5.71	21.82	724.75	923.52
202	.256	.0694	5.42	20.43	776.82	1003.6
	$\overline{(I/w^{1/3})} = 763.23$			$\sigma = 6.478$		
			1/2-lb Pentolite (approximately)			
203	.527	.0731	4.12	20.00	834.86	837.23
204	.527	.0721	4.19	a	820.92	--
205	.525	.0721	4.25	20.59	810.29	814.16
206	.527	.0716	4.24	20.27	805.58	820.20
207	.524	.0716	4.05	18.34	845.53	908.98*
208	.519	.0714	4.10	a	835.98	--
209	.522	.0710	4.21	20.04	807.58	825.86
210	.522	.0710	4.47	19.85	807.20	831.44
211	.522	.0705	4.08	19.84	827.47	828.37
212	.522	.0705	b	a	--	--
213	.523	.0741	4.29	20.91	825.96	824.95
214	.522	.0745	4.40	21.22	810.76	817.00
	$\overline{(I/w^{1/3})} = 822.70$			$\sigma = 11.52$		
			1-lb Pentolite			
215	1.070	.119	5.71	28.04	785.03	777.52
216	1.066	.122	6.45	28.38	713.15*	788.60
217	1.074	.119	5.98	27.90	748.55	780.54
218	1.069	.121	5.95	a	766.20	--
	$\overline{(I/w^{1/3})} = 774.40$			$\sigma = 14.82$		

Note:

a - no counter reading
b - no film reading
* - rejected as an outlying observation
** - plug area $= \pi/4$ in. throughout the tests.
\# - discarded complete column

$\overline{Z} = 1$

1/4-lb Pentolite (approximately)

Rd. No.	w_e	w_p	δt_f	δt_c	$I_f/w_e^{1/3}$	$I_c/w_e^{1/3}$
53	.257	.0675	18.30	86.61	221.12	224.39
54	.256	.0675	19.60	87.41	206.33	222.60
55	.257	.0675	19.00	89.43	212.77	216.92
56	.257	.0675	18.20	84.68	222.30	229.76
57	.258	.0675	18.60	87.21	217.08	222.49
158	.255	.0677	17.88	84.31	227.90	232.30
159	.257	.0677	19.35	90.81	209.60	214.30
160	.256	.0677	19.05	90.54	213.20	215.30
161	.252	.0677	18.23	86.05	224.20	228.20
162	.257	.0677	17.33	81.58	234.60	239.80

$\overline{(I/w^{1/3})} = 221.76$ $\sigma = 8.712$

1/2-lb Pentolite (approximately)

Rd. No.	w_e	w_p	δt_f	δt_c	$I_f/w_e^{1/3}$	$I_c/w_e^{1/3}$
146	.529	.0672	14.00	64.42	229.83	239.06
147	.532	.0672	13.50	65.51	235.78	234.81
148	.525	.0672	13.70	65.26	232.94	236.31
149	.524	.0672	b	66.86	--	231.02
150	.524	.0672	13.20	65.16	242.23	237.34
151	.522	.0672	14.20	66.17	225.35	233.66
152	.525	.0672	b	a	--	--
153	.518	.0672	b	58.92	--	264.01*
154	.519	.0672	13.90	66.85	230.88	231.88
155	.525	.0672	14.00	65.74	229.74	234.70
156	.524	.0672	13.50	64.01	236.95	241.56
157	.535	.0672	13.50	63.89	235.20	240.15

$\overline{(I/w^{1/3})} = 234.70$ $\sigma = 4.375$

$\bar{Z} = 1$

1-lb Pentolite (approximately)

Rd. No.	W_e	W_p	δt_f	δt_c	$I_f/W_e^{1/3}$	$I_c/W_e^{1/3}$
45	1.052	.0668	b	52.53	--	232.54
46	1.053	.0668	11.00	54.47	229.13	224.07
47	1.054	.0668	10.30	a	244.60	--
48	1.058	.0668	10.50	50.84	239.68	239.93
49	1.064	.0668	10.60	53.17	236.90	228.80
50	1.044	.0668	12.30	58.64	205.28	208.44
51	1.060	.0675	10.60	50.50	239.82	244.10
52	1.065	.0675	10.80	52.41	235.15	234.42
85	1.066	.0665	10.30	48.00	242.70	257.79
86	1.073	.0665	10.30	49.53	242.70	244.32
87	1.059	.0665	11.70	55.67	214.09	217.97
88	1.057	.0663	12.20	57.04	205.25	212.17
89	1.062	.0663	11.20	54.09	222.63	223.56

$\overline{(I/W^{1/3})} = 230.25$ $\sigma = 14.20$

2-lbs Pentolite (approximately)

Rd. No.	W_e	W_p	δt_f	δt_c	$I_f/W_e^{1/3}$	$I_c/W_e^{1/3}$
58	1.962	.0675	8.52	43.13	243.43	232.86
59	1.962	.0675	9.90	47.99	209.31	209.44
60	1.941	.0670	9.16	41.52	225.53	241.68
61	1.970	.0672	7.76	36.77	265.96	272.77
62	1.957	.0672	9.30	45.43	222.26	220.78

$(I/W^{1/3}) = 234.40$ $\sigma = 21.77$

$\bar{Z} = .75$

1/4-lb Pentolite

Rd. No.	w_e	w_p	δt_f	δt_c	$I_f/w_e^{1/3}$	$I_c/w_e^{1/3}$
174	.254	.0634	b	a	--	--
175	.257	.0679	10.97	52.98	374.4	375.6
176	.255	.0679	11.01	47.56	373.8	420.5*
177	.258	.0679	11.24	52.34	365.3	380.3
178	.257	.0679	11.08	53.07	370.6	375.0
179	.257	.0679	11.00	52.11	373.4	381.9
180	.255	.0681	11.12	52.11	370.5	383.1
181	.255	.0681	11.30	a	364.5	--
182	.257	.0681	11.13	52.87	368.9	376.4
183	.256	.0683	11.35	53.14	363.6	380.6
184	.257	.0683	10.97	52.70	375.8	379.1
227	.251	.0688	10.70	52.74	391.4	384.7
228	.252	.0688	10.80	52.00	387.1	389.7
229	.253	.0692	11.40	55.01	368.9	370.3
230	.257	.0692	11.50	54.03	363.4	374.8
231	.256	.0692	10.90	52.60	384.2	385.8

$\overline{(I/w^{1/3})} = 376.2$ $\sigma = 8.084$

1/2-lb Pentolite (approximately)

Rd. No.	w_e	w_p	δt_f	δt_c	$I_f/w_e^{1/3}$	$I_c/w_e^{1/3}$
163	.523	.0677	9.24	44.33	349.7*	353.7*
164	.532	.0677	8.54	40.88	376.2	385.4
165	.520	.0677	8.44	41.21	383.9	382.0
166	.517	.0677	8.68	41.09	373.8	383.4
167	.524	.0677	8.24	39.76	392.3	395.0
168	.527	.0677	8.50	40.88	379.0	385.9
169	.523	.0677	8.65	41.07	374.1	382.4
170	.517	.0677	8.33	a	389.4	--
171	.526	.0677	8.91	a	362.3	--
172	.518	.0677	8.70	a	372.7	--
173	.523	.0679	8.79	a	369.5	--
238	.519	.0692	8.50	40.70	389.7	395.3
239	.523	.0692	8.50	40.98	388.8	391.6
240	.523	.0697	8.40	40.42	395.9	399.7
241	.527	.0697	8.50	40.87	390.5	394.4

$\overline{(I/w^{1/3})} = 384.7$ $\sigma = 9.168$

$\overline{Z} = .75$

1-lb Pentolite (approximately)

Rd. No.	w_e	w_p	δt_f	δt_c	$I_f/w_e^{1/3}$	$I_c/w_e^{1/3}$
90	1.064	.0663	6.75	32.30	370.5	376.4
91	1.068	.0663	7.70	37.40	324.0	324.1
92	1.074	.0663	7.30	35.19	341.3	344.3
93	1.071	.0672	b	35.50	--	345.4
94	1.061	.0672	6.45	31.89	393.5	387.2
96	1.052	.0672	7.05	33.31	360.5	371.3
97	1.062	.0672	7.05	33.41	360.2	370.0
188	1.070	.0672	6.75	32.01	374.7	384.2
189	1.070	.0670	7.13	33.92	353.7	361.5
192	1.070	.0680	7.44	35.74	343.9	348.0
193	1.060	.0690	7.25	34.08	359.4	371.2

$\overline{(I/w^{1/3})} = 360.3$ $\sigma = 19.03$

$\overline{Z} = 1.50$

1/4-lb Pentolite

Rd. No.	w_e	w_p	δt_f	δt_c	$I_f/w_e^{1/3}$	$I_c/w_e^{1/3}$
136	.256	.0672	31.1	143.05	126.91	129.44
137	.256	.0672	31.0	142.38	127.34	130.24
138	.258	.0672	32.0	146.53	122.96	125.94
139	.256	.0672	32.6	149.89	120.65	122.68
140	.258	.0672	31.7	145.91	130.90	126.26
141	.258	.0672	31.0	143.20	127.14	129.25
142	.257	.0672	32.9	151.93	119.20	120.44
143	.254	.0672	30.7	140.48	129.00	132.39
144	.258	.0672	31.1	142.86	126.71	129.71
145	.257	.0672	34.2	155.09	114.17	117.45
221	.256	.0688	34.8	a	115.01	--
222	.256	.0688	39.4	180.74	100.26*	100.14*
223	.256	.0688	34.1	154.09	117.54	121.48
224	.257	.0688	34.9	155.79	114.50	119.70
225	.257	.0688	30.9	143.47	130.53	131.76
226	.257	.0688	34.3	156.51	116.64	119.06

$\overline{(I/W^{1/3})} = 123.97$ $\sigma = 5.091$

1/2-lb Pentolite

Rd. No.	w_e	w_p	δt_f	δt_c	$I_f/w_e^{1/3}$	$I_c/w_e^{1/3}$
124	.521	.0672	b	112.41	--	124.62
125	.521	.0672	24.6	114.83	128.16	121.73
126	.528	.0672	23.0	107.54	136.95	130.32
127	.522	.0672	23.6	109.90	133.78	127.70
128	.525	.0672	23.2	109.26	135.85	128.20
129	.527	.0672	22.5	104.99	140.02	133.66
130	.529	.0672	24.2	112.90	129.73	123.41
131	.519	.0672	24.4	113.23	129.58	123.93
132	.526	.0672	23.7	111.83	132.92	125.02
133	.522	.0672	24.0	111.82	131.50	125.33
134	.512	.0672	22.7	105.44	140.20	134.39
135	.519	.0672	23.3	109.05	135.93	129.13
263	.520	.0694	b	115.05	--	134.75
264	.526	.0694	26.0	119.26	124.62	129.03
265	.528	.0694	24.5	114.34	133.88	134.95
266	.527	.0694	24.2	113.15	135.70	136.60
267	.529	.0694	25.6	117.85	127.97	130.48

$\overline{(I/w_e^{1/3})} = 130.94$ $\sigma = 4.955$

$\overline{Z} = 1.50$

1-lb Pentolite

Rd. No.	w_e	w_p	δt_f	δt_c	$I_f/w_e^{1/3}$	$I_c/w_e^{1/3}$
6	1.063	.0659	18.30	a	134.8	--
9	1.068	.0659	17.80	92.16	138.3	127.6
10	1.053	.0659	17.80	84.43	139.3	140.1
11	1.051	.0659	19.00	90.70	130.5	131.0
12	1.046	.0659	18.00	88.70	137.7	134.0
13	1.046	.0659	19.00	90.10	130.5	131.8
14	1.047	.0659	18.30	86.20	135.3	138.0
30	1.060	.0688	19.70	33.36	126.3	367.2*
31	1.049	.0688	18.60	88.65	134.6	135.6
32	1.069	.0688	19.50	33.33	127.8	366.5*
33	1.078	.0688	16.60	77.41	149.7	154.9
34	1.052	.0688	18.90	a	132.8	--
35	1.052	.0688	18.50	46.57	135.6	263.2*
36	1.050	.0688	19.50	91.72	128.3	130.7
37	1.058	.0688	9.42	94.19	[illegible]17.2*	126.6
63	1.054	.0663	18.72	89.07	132.55	133.71
64	1.054	.0663	15.43	84.43	164.07*	141.45
65	1.064	.0663	19.04	91.77	129.91	129.17
66	1.057	.0663	18.74	89.23	132.30	133.32
67	1.047	.0663	18.75	89.30	132.74	133.75
68	1.058	.0663	18.00	86.82	137.89	137.21
69	1.061	.0663	b	85.33	--	139.60
70	1.059	.0663	16.00	80.86	152.89	147.84
71	1.044	.0663	17.35	83.77	146.45	143.17
72	1.054	.0663	b	90.74	--	131.11
73	1.041	.0663	b	89.57	--	133.44

$\overline{(I/w^{1/3})} = 135.72$ $\sigma = 6.829$

$Z = 2$

1/2-lb Pentolite

Rd. No.	w_e	w_p	δt_f	δt_c	$I_f/w_e^{1/3}$	$I_c/w_e^{1/3}$
250	.523	.0701	37.1	a	86.09	--
251	.525	.0701	37.4	a	85.26	--
252	.522	.0701	40.0	181.61	79.28	80.02
253	.518	.0701	38.0	171.94	84.16	85.89
254	.527	.0701	42.2	187.79	74.33	76.23
255	.524	.0701	40.0	180.83	79.19	80.36
256	.531	.0701	43.5	194.59	71.65	72.88

$\overline{(I/w_e^{1/3})} = 79.61$ $\sigma = 5.072$

1-lb Pentolite

Rd. No.	w_e	w_p	δt_f	δt_c	$I_f/w_e^{1/3}$	$I_c/w_e^{1/3}$
257	1.070	.0701	32.0	a	79.68	--
258	1.058	.0701	29.2	134.53	88.21	90.23
259	1.065	.0701	30.2	140.45	84.92	85.72
260	1.066	.0701	28.0	130.85	90.94	92.81
261	1.052	.0701	40.2	a	62.35*	--
262	1.076	.0701	30.1	a	84.91	--

$\overline{(I/w_e^{1/3})} = 87.18$ $\sigma = 4.223$

$\overline{Z} = 2.50$

1/4-lb Pentolite

Rd. No.	w_e	w_p	δt_f	δt_c	$I_f/w_e^{1/3}$	$I_c/w_e^{1/3}$
26	.258	.0668	72.0	324.61	45.2	38.9
27	.255	.0668	80.6	308.94	38.0	43.4
28	.258	.0668	76.6	312.66	41.1	42.2
29	.255	.0668	71.5	296.60	46.0	46.7
107	.256	.0668	65.7	a	52.0	--
108	.255	.0668	73.8	a	43.8	--
109	.253	.0668	72.2	a	45.6	--
110	.257	.0668	70.4	a	46.9	--
111	.255	.0668	65.4	272.00	52.5	54.5
112	.258	.0668	b	a	--	--
113	.257	.0668	64.0	270.00	53.6	55.1
114	.258	.0668	b	282.00	--	55.1
115	.256	.0668	b	273.00	--	54.1
116	.255	.0668	66.8	282.00	50.9	51.3

$\overline{(I/w^{1/3})} = 47.6$ $\sigma = 5.366$

1/2-lb Pentolite

Rd. No.	w_e	w_p	δt_f	δt_c	$I_f/w_e^{1/3}$	$I_c/w_e^{1/3}$
117	.532	.0672	50.9	a	57.10	--
118	.524	.0672	54.9	a	52.10	--
119	.526	.0672	55.3	a	51.70	--
120	.524	.0672	55.0	a	52.10	--
121	.527	.0672	50.7	a	57.60	--
122	.526	.0672	54.8	a	52.40	--
123	.526	.0672	51.3	a	56.70	--
232	.523	.0692	b	265.63	--	46.24
233	.518	.0692	54.6	237.44	54.40	55.18
234	.529	.0692	55.8	236.48	52.53	55.14
235	.525	.0692	61.0	255.10	46.92	49.27
236	.530	.0692	b	240.86	--	53.64
237	.520	.0692	55.5	240.57	53.33	54.05

$\overline{(I/w_e^{1/3})} = 52.96$ $\sigma = 3.202$

$\overline{Z} = 2.50$

1-lb. Pentolite

Rd. No.	w_e	w_p	δt_f	δt_c	$I_f/w_e^{1/3}$	$I_c/w_e^{1/3}$
38	1.046	.0668	b	a	--	--
39	1.046	.0668	45.0	201.89	52.50	52.80
40	1.051	.0668	33.2	33.18	71.00	370.70*
41	1.057	.0668	97.0	210.40	16.10*	49.70
42	1.056	.0668	43.8	194.40	53.84	55.26
43	1.049	.0668	44.3	199.77	53.19	53.44
44	1.052	.0668	43.3	192.35	54.56	56.07
98	1.069	.0672	41.4	185.79	59.36	65.78
99	1.065	.0672	41.5	183.15	59.14	66.89
100	1.072	.0672	40.1	a	61.46	--
101	1.068	.0672	42.1	a	61.25	--
102	1.072	.0672	40.1	179.33	61.28	68.13
103	1.070	.0672	43.5	193.10	56.34	67.93
104	1.062	.0672	39.7	176.40	56.53	63.24
105	1.070	.0672	40.0	178.06	61.62	69.61
106	1.074	.0672	37.7	168.95	66.76	72.36

$\overline{(I/w_e^{1/3})} = 60.39$ $\sigma = 6.548$

2-lb. Pentolite

Rd. No.	w_e	w_p	δt_f	δt_c	$I_f/w_e^{1/3}$	$I_c/w_e^{1/3}$
21	1.979	.0668	30.3	135.12	65.6	69.3
22	1.974	.0668	33.5	32.57	58.9	305.9*
23	1.961	.0668	31.0	a	64.1	--
24	1.963	.0668	32.5	146.81	61.0	63.3
25	1.978	.0668	34.0	152.50	58.0	60.4

$\overline{(I/w_e^{1/3})} = 62.6$ $\sigma = 3.758$

The mean scaled impulse $(I/W^{1/3})$ and standard deviation σ were calculated for each charge weight and Z and these results are presented in Table I along with the data on the individual rounds. By using the F test* at the one per-cent level, it was found that for each Z a grand mean (i.e., average of all the charge weights) and standard deviation could be calculated for all Z's except Z = 2.5. These grand means and standard deviations appear in Table II and also in Figure 12 where gage data and plug data are compared.

TABLE II

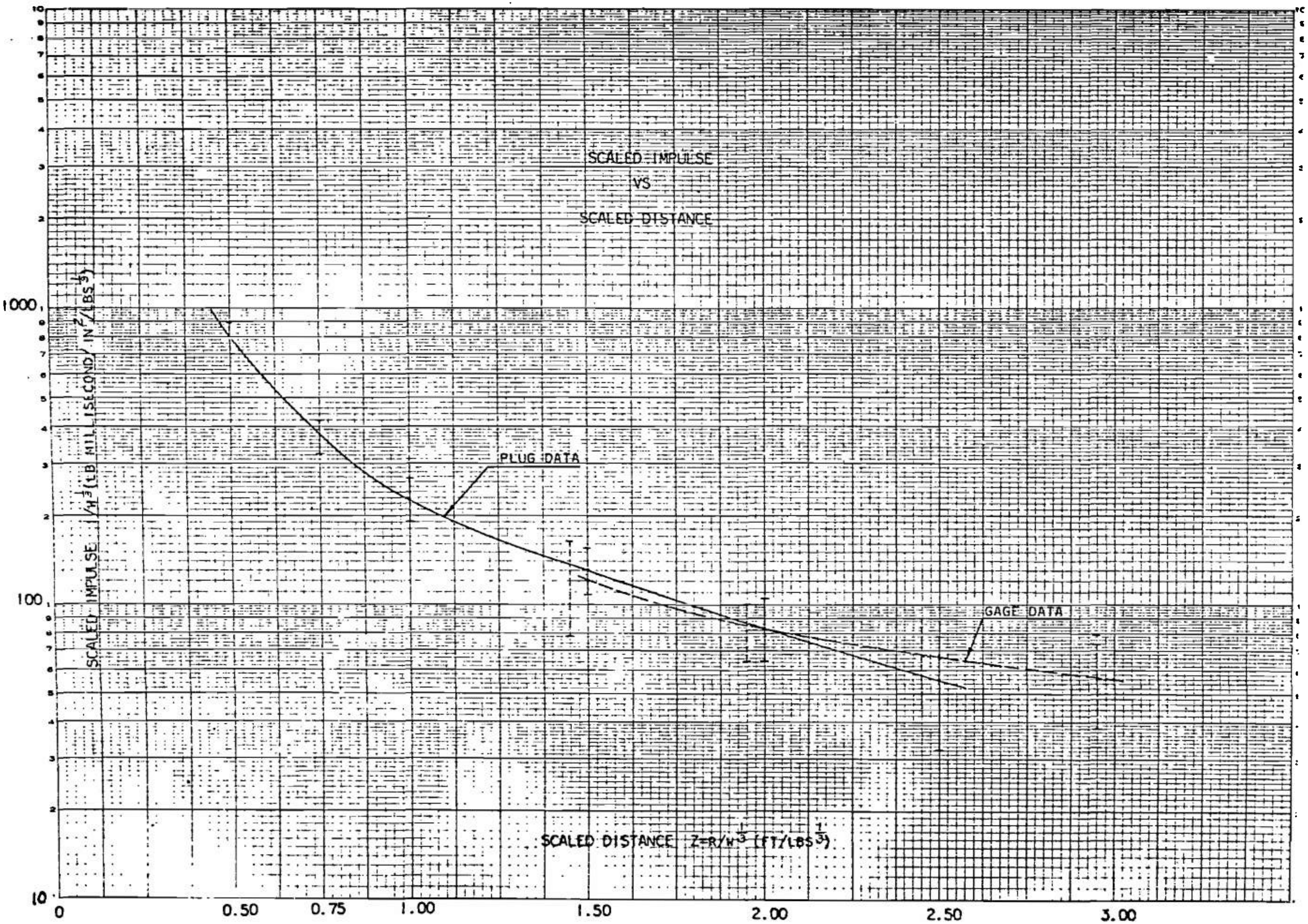
Z	.5	.75	1.0	1.5	2.0
$I/W^{1/3}$	795.58	374.40	229.65	130.92	82.64
3σ	96.60	47.02	39.78	22.84	17.98

Figure 12 presents the results in graphical form (solid curve) together with previously reported BRL data on reflected impulse[3a] taken with piezo-electric gages (dashed curve). It should be noted that different curve-fitting techniques were used for the two sets of data. The curve of the present test results is an eye fit of the scaled impulse grand mean versus Z, while Hoffman and Mills data were fitted by plotting the weighted** averages of the coordinates associated with groups of points. The results of the previous measurements of reflected impulse made by Hoffman and Mills[3a] extended over the range Z = 1.5 to Z = 15. The results reported here can be used to extend this range down to Z = 0.5. A curve representing the best estimate of reflected impulse based on Hoffman and Mills' data and the current data is presented as Figure 13.

The assumption that plug motion was small during the pressure pulse can be shown to be well verified. Table III gives the results of applying Equation (11a) for the displacement to some representative test results. Note that the maximum displacement at the end of the blast pulse was only slightly greater than one-eighth of an inch, and therefore quite inconsequential.

* The F test is a test of the hypothesis that a number of samples are derived from the same normal population.

** Weighted according to the number of observations.



SCALED IMPULSE
VS
SCALED DISTANCE
PLUG DATA
GAGE DATA
SCALED IMPULSE $I/W^{\frac{1}{3}}$ (LB MILLISECOND/ IN^2/$LBS^{\frac{1}{3}}$)
SCALED DISTANCE $Z=R/W^{\frac{1}{3}}$ (FT/$LBS^{\frac{1}{3}}$)
1000
100
10
0
0.50
0.75
1.00
1.50
2.00
2.50
3.00

FIGURE 12

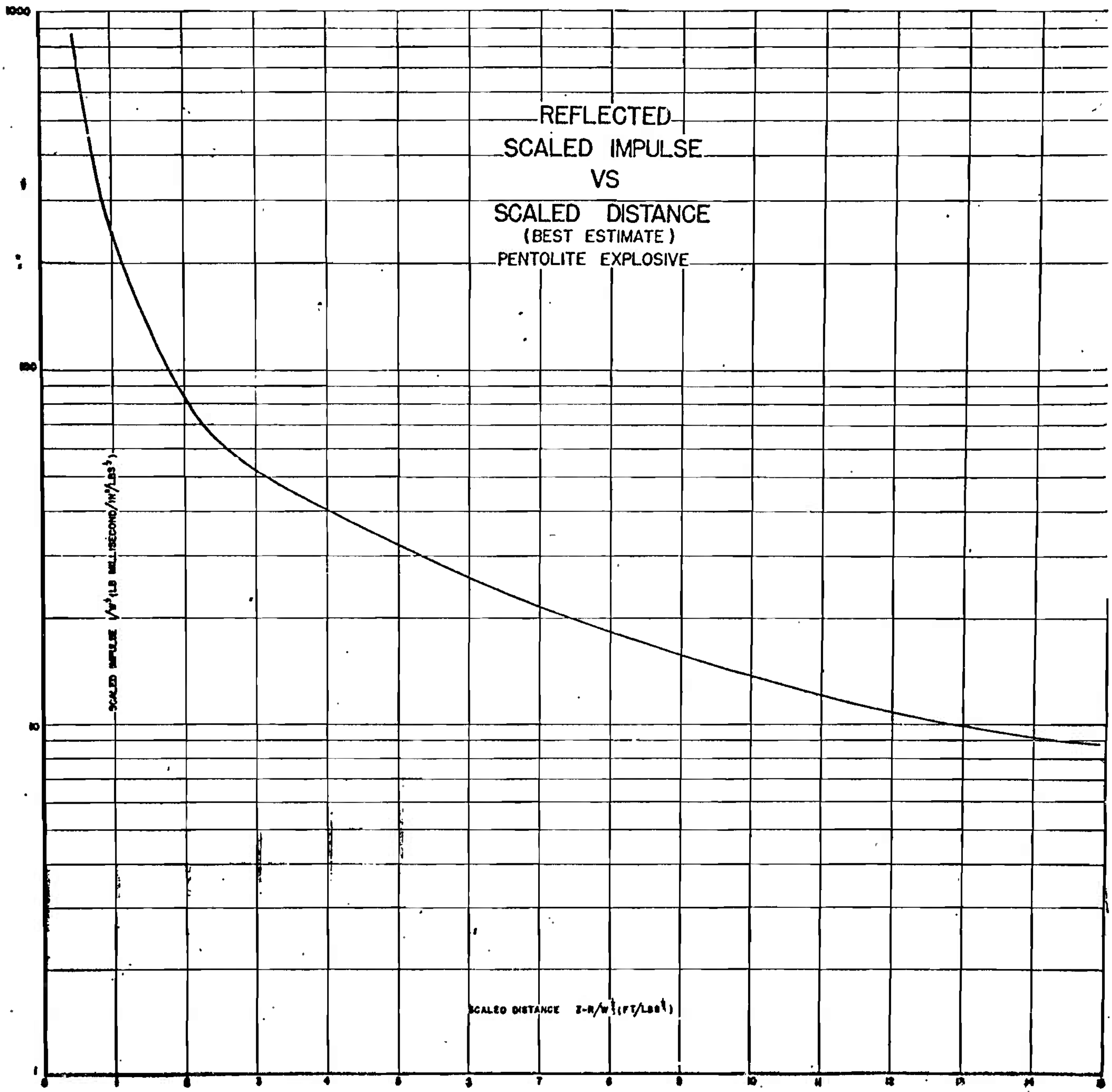

REFLECTED
SCALED IMPULSE
VS
SCALED DISTANCE
(BEST ESTIMATE)
PENTOLITE EXPLOSIVE
SCALED DISTANCE

FIGURE 13

TABLE III

Displacement, x(T), at End of Blast Pulse

Z	w_e	w_p	x(T) in inches
0.5	0.255	0.069	0.072
0.5	0.525	0.072	0.122
0.5	1.07	0.120	0.109
1.0	0.255	0.068	0.032
1.0	0.525	0.067	0.056
1.0	1.07	0.067	0.088
1.0	1.96	0.067	0.132
2.5	0.255	0.067	0.017
2.5	0.525	0.068	0.031
2.5	1.07	0.067	0.057
2.5	1.96	0.067	0.089

DISCUSSION

The results of these tests show the usefulness of the moving plug experimental technique for measurement of reflected scaled impulses close to explosive charges. The data presented in the tables and figures represent the first reliable measurements of this parameter for scaled distances less than 1.5 ft/lb$^{1/3}$. The results also show that Sachs' scaling[6] for reflected impulse is valid under sea level ambient conditions for scaled distances as small as 0.5.

The concept of using simple mechanical gages for impulse measurements is by no means new. It is reported in reference 7 that Prof. K. Muto of the Tokyo Imperial University determined blast impulses by measuring the horizontal distance a cube was projected when placed on a support above the ground and subjected to an impulse from the side. A double pendulum type of impulse gage is also mentioned in this report. Reiner[8] also discusses a device for measuring impulse by projecting a ball horizontally. The aforementioned reports are only two of many which suggest the use of this technique or a similar one. The value of the work reported here lies in the perfection of the technique to a point where it can not only supplement techniques requiring much more complicated instrumentation, but even supplant them in regions of very intense, short duration pressure loadings.

In the Introduction it was mentioned that past experiments indicated face-on impulse is an important parameter relating to blast damage, especially internal blast, and it is possible that further investigation may assign the same level of importance to face-on impulse when considering external blast damage. BRLM 1036 indicates[4] that at extremely close distances (scaled distances less than 2.0) the use of Sachs'[6] scaling law fails when attempting to predict the I_f necessary to do a desired amount of damage under some simulated conditions of altitude. Plans have been initiated to conduct a test, similar to the one described in this report, at reduced pressures simulating altitudes of 30 and 60 thousand feet to test the validity of Sachs' scaling at small scaled distances at these altitudes.

At this time firings have commenced using H-6 in place of Pentolite in order to determine whether the plug device is suitable for evaluating explosives.

ACKNOWLEDGMENTS

The authors of this report wish to gratefully acknowledge the assistance of Mr. Victor Weingarten, who conducted the feasibility phase of this effort. In addition gratitude is extended to Mr. Frank Thompson, Mr. Henry Goodman, and Miss Perea McCane for their able assistance in the analysis and reduction of the experimental data.

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